MCR-91-1341
Contract NAS8-36431

Phase IV
Final Report

October 1991

Intelligent Robotic Systems Study (IRSS)

(NASA-CR-184262) INTELLIGENT ROBOTIC SYSTEMS STUDY (IRSS), PHASE 4 Final Report (Martin Marietta Space Systems) 52 p

N92-14672

CSCL 09B

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G3/63 0053189

MARTIN MARIETTA

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INTELLIGENT ROBOTIC SYSTEMS STUDY (IRSS)

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Acronym List

C-H	Cooper-Harper
DOF	Degree(s) of Freedom
FTS	Flight Telerobotic Servicer
HCI	Human Computer Interface
LED	Light Emitting Diode
MANOVA	Multivariate Analysis of Variance
MIS	Management Information Systems
MSFC	Marshall Space Flight Center
NASREM	NASA/NBS Standard Reference Model for Telerobot Control System Architecture
OMV	Orbital Maneuvering Vehicle
ORU	Orbital Replacement Unit
PFMA	Proto-Flight Manipulator Arm
RMS	Root Mean Square
TP	Task Panel

1.0 Introduction

1.1 IRSS System Overview

Under the Intelligent Robotics System Study (IRSS) contract, a generalized robotic control architecture has been developed for use with the ProtoFlight Manipulator Arm (PFMA) which resides at Marshall Space Flight Center (MSFC) in Huntsville, Alabama. Based upon the NASREM system design concept, the controller built for the PFMA provides localized position based force control, teleoperation and advanced path recording and playback capabilities. Various hand controllers can be used with the system in conjunction with a synthetic time delay capability to provide a realistic test bed for typical satellite servicing tasks.

The PFMA has six computer controllable degrees of freedom (DOF) plus a seventh manually indexable DOF, making the manipulator a pseudo 7 DOF mechanism. Because the PFMA was not developed to operate in a gravity field, but rather in space, it is counter balanced at the shoulder, elbow and wrist and a spring counterbalance has been added near the wrist to provide additional support. Built with long slender intra-joint linkages, the PFMA has a workspace nearly 2 meters deep and possesses sufficient dexterity to perform numerous satellite servicing tasks. The manipulator is arranged in a shoulder-yaw, pitch, elbow-pitch, and wrist-pitch, yaw, roll configuration, with an indexable shoulder roll joint.

Joints on the PFMA are driven via 7 pulse width modulated amplifiers(6 DOF + end effector). Resolvers and tachometers are used to measure relative joint positions and velocities. Motor drive currents are controlled via analog inputs to joint amplifier cards, and analog outputs are provided that feedback actual motor currents to the PFMA controller. Currently, there are two hand controllers for the PFMA: a compact rate (CAE) hand controller and a larger hand controller developed by Seargent Laboratories which has force feedback capabilities. A Lord Force/Torque Sensor mounted to the manipulator near its end effector is used to implement various force-based control schemes and eventually force reflection.

Digital control of the PFMA is implemented using a variety of single board computers developed by Heurikon Corporation and other manufacturers. The digital hardware architecture is comprised of five Heurikon V2F processor cards (68020 based) in a single 32 bit VME chassis connected to a second 24 bit VME chassis via a shared memory card. The first chassis (the computational chassis) performs all controls computations and operates the user interface. The second chassis contains all the electronics that interface directly to the PFMA and hand controllers. This chassis uses a Motorola MVME 104 processor card (68010 based) to perform all system data acquisition. Because of its function, this second chassis is called the Input/Output (I/O) chassis.

1.2 Scope of Phase IV Effort

There were two major activities under the IRSS phase IV contract:

1) Enhancement of the PFMA control system software functionality;

2) Evaluation of operating modes via a teleoperation performance study.

These activities are described in sections 2 and 3 respectively.

2.0 Control System Software

The following sections describe updates and enhancements made to the IRSS control software as part of the IRSS phase IV effort. Upgrades and modifications performed for this phase of the contract can be grouped into three principal areas. These categories are: Enhanced Operator Interface, Control System Upgrades and System Simulation Capabilities. Each of these areas may be further subdivided into a list of specific tasks which were performed to accomplish each.

- Integration of the VPL data glove hand controller into the robot control system.
- Integration of the Fluke 1031 touchscreens into the user interface.
- Real-time kinematic simulation of the robotic manipulator using the Evans & Sutherland PS-390 interactive graphics computer.
- Alternative PFMA joint reference generators were implemented.
- Enhanced data recording capabilities were integrated into the PFMA robot controller.
- Software/hardware related problems were identified and addressed.
- Analysis, design and preliminary implementation of a limited bandwidth bidirectional communications link between a remote robotic servicer and a ground based user interface were performed.
- Off-line system simulation capabilities were upgraded to support off-site update and debug of IRSS system software.

2.1 Enhanced Operator Interface

2.1.1 VPL Data Glove Integration.

A spandex glove instrumented with a variety of sensors was integrated into the IRSS robot controller for use as a teleoperation input device. Due to the unique nature of this user input mechanism, it was anticipated that much could be learned as the glove was used to move the robot through its work environment performing various tasks. What makes the data glove so unique is that it has a much larger work volume than almost any mechanical hand controller, not to mention that it also possesses a very low inertia (a rather uncommon feature among hand controllers). This glove, developed and marketed by VPL Corporation, uses three separate types of sensors to determine a variety of conditions pertaining to the users hand position. A Polhemus electromagnetic emitter/detector pair uses a multiplexed magnetic field to determine relative position and orientation of the glove within the hand controller work envelope. This is used to control gross robot position and orientation changes. Sixteen fiber optic flex sensors are mounted on the glove and are used to determine relative flexure of knuckles and the position of the thumb. This is used for controlling the end effector operations and virtual deadman switch (to perform ratcheting) for the robot. A final sensor set measures the relative distance between the tip of the index finger and the thumb (this sensor is not presently in use).

The VPL data glove is tied to the IRSS control computer via a 9600 baud, RS-232 serial link passing data to a MVME-410 card within the system VME I/O chassis (see the IRSS phase II final report[1] for a discussion of this chassis). Currently, six integer values representing glove Cartesian positions and orientation, and ten flex sensor values (2 for each finger and the thumb) are being returned to the I/O computer at a 30 Hz rate. Orientations are input to the chassis in a yaw-pitch-roll format. Though while the I/O chassis is operating data acquisition from the data glove is constantly occurring, this data is only processed when data glove teleoperation is active. The resolution of incoming data is sufficient to permit the teleoperation of smooth robot slewing motions throughout the entire manipulator workspace.

Using software developed for the data glove, a user defined virtual box is oriented around and located behind the glove's Polhemus emitter. With the glove inside this virtual box, when the thumb is curled tightly toward the palm, the PFMA can be teleoperated in a variety of modes including rate, position, and "hawk" (translations only mode). High and low gain settings for these various modes are correlated directly to middle and index finger positions as transduced by the glove's fiber optic flex sensors. High gain is achieved when both fingers are extended, low gain when only the index finger is extended. Flexing all fingers back commands the end effector jaws to open while curling all fingers toward the palm affects closure. Any glove gestures made when the glove is outside of the virtual box about the emitter are ignored by teleoperation algorithms. An interactive parameters menu permits the user to adjust various gain values and dictate thumb-deadman and finger-end effector open/close operational thresholds. Raw data coming from the data glove can be seen using hardware diagnostics provided in the IRSS software.

Preliminary exercises with the data glove appear to demonstrate that it is well suited for the control of robotic manipulators like the PFMA. Although the RS-232 serial link between the data glove and the I/O computer functioned very reliably, this input device was shown to have other rather troubling idiosyncrasies with regards to the magnetic fields which it generates. The most prominent had to do with the Polhemus emitter used to determine the glove's orientation and position. When this emitter was placed close to metal objects (e.g. metal desks and chairs) warping of its emission field caused the hand controller to behave abnormally along certain axis. In

[1]Intelligent Robotic Systems Study (IRSS): Phase II Final Report, Martin Marietta, MCR-89-559, contract NAS8-36431, May 1990.

addition, it was determined that operating the VPL glove in close proximity to the system I/O chassis appears to induce electrical noise onto the VME backplane causing failure of system bus read and write cycles; a very serious problem. To optimize the operation of the data glove more effort is needed to calibrate operational axial gains for use in all modes that the controller can function in. This is necessary to guarantee the safety of the PFMA and fragile task panels.

A preliminary application of neural networks to help classify gestures and commands was performed. Although algorithms for their use were not integrated into the IRSS controller, a small amount of data was collected and used with a simple network. The results were very promising. Rapid convergence during training and distinctive recognition of gestures was achieved for all gestures in each of four data sets collected.

2.1.2 Fluke 1031 Touch Screen Integration

The new human-computer (HCI) system and associated screens allow the operator to easily operate the PFMA. The hierarchy for the new HCI system is shown in Figure 2-1. The new HCI design provides an easy to use, hierarchical operator interface. In the Help, Demo, and Test hierarchies, the operator is provided with prompts to guide him/her through the hierarchies. These hierarchies provide the operator with two methods of command entry—touchscreen and keyboard input. The Program hierarchy screens do not provide prompts to guide the operator though the hierarchy and provides primarily a keyboard entry interface. The Program hierarchy provides less guidance to accommodate the skill level of experienced programmers who will be using this hierarchy of screens.

This HCI design was implemented by adding two Fluke 1031 touch terminal monitors to the previous IRSS operator interface. Using graphics characters and resident highlighting and font capabilities present in these terminals a simplified user interface was added to the IRSS robot control system. Using these terminals many macro operations requiring many keystrokes from the engineering console were consolidated under a single touch key.

The two touch terminals are physically connected to the Heurikon real-time control computer via 9600 baud RS-232 serial links (through the XYcom quad serial port card). The program which operates the user interface routinely queries each of the touch screens to determine if the user has selected an operation through either touch or by having typed a letter at the touch screen keyboard. Operations coming from the touch screens behave just as they would if they came through the engineering console terminal. Functionality is divided between the two touch screens with the first operating as the sole operations command screen and the second providing a system monitor and display function.

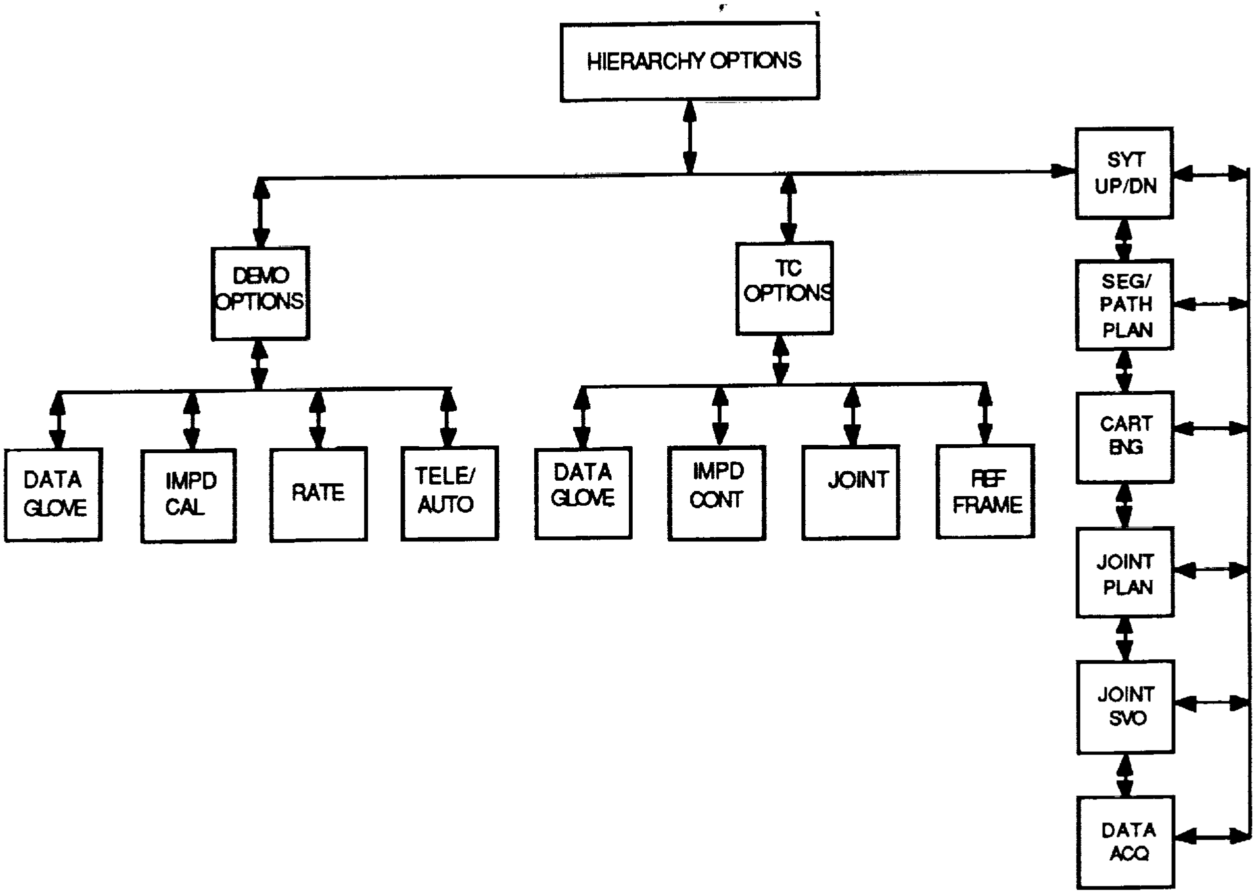

Figure 2-1. Touch Screen Hierarchy

The system command touch terminal provides four primary menus used to control the PFMA in a number of modes and using various hand controllers. Additional menus are provided that allow the user to move from menu to menu. Stubs for future operational menu integration have also been provided. Typically, operational menus provide selection of impedance parameters from a choice of four options, selection of hand controller operational modes and gains and execution of one of up to four autonomous path primitives. Touch menus for both the VPL data glove and the CAE hand controller are provided. One of the touch screens is designed specifically for the analog like calibration of impedance parameters using either the CAE or the VPL data glove hand controller. A topological map of the touch screen menu tree is provided via a touch key common to almost every screen.

The system monitor and display touch screen allows the user direct visibility of system variables associated with each of the functional layers of the IRSS control system (for a definition of these layers see the IRSS phase II final report). These displays are updated at near real time rates to provide accurate internal system information. Help information is available at the touch of a key. This real-time monitoring function can also be disabled via an active touch key. With this monitoring and display function disabled operator input bandwidth via the engineers console is improved.

The entire Fluke touch screen interface is built upon a standard touch screen library designed to operate the touch terminals and design custom menus with a minimum of effort. Standard utilities for the display of real time menus were adapted for use with these terminals reducing the overall amount of code that had to be developed. This interface library should be portable to other hardware systems (e.g. PCs or VAXs) so that almost any system with a C compiler, the support library and a serial port can function as a host. This support library provides primitive functions such as complete touch key definitions, line drawing and text processing.

2.1.3 Real-time Kinematic Simulation of the PFMA

With a variety of mechanical limitations which the PFMA has, the robot controller can sometimes appears to be malfunctioning. These physical limitations include stiction in both the joint motor drive trains and the spring counterbalance supporting the robot's wrist, as well as limitations on the maximum amount of torque that the PFMA's joints can generate. This manifests itself in teleoperation, for instance, when commanded motions from a hand controller appear to have to no effect on the robots position. To enhance the operator interface, help understand some of the physical limitations of the mechanical system and provide the capabilities to playback autonomous path primitives before they are executed, a graphical kinematic simulation of the PFMA was developed. In this simulation a wire-frame image of the PFMA is displayed indicating the commanded positions of each of the robot's joints and end effector. This graphics display can be scaled, and the observation point from which the simulation is viewed can be modified using several dials provided with the graphics computer, an Evans & Sutherland PS-390 graphics workstation.

This simulation is driven via an RS-232 link connecting the Heurikon computational chassis (using the XYcom quad serial port card) to the serial input port of the E&S PS-390. After the preliminary wire frame model of the PFMA is downloaded to the PS-390, the computer is periodically passed the commanded joint angles of the PFMA. This provides real-time animation of the robot's motion. This simulation can be driven using either teleoperation (CAE or Data Glove hand controller) or autonomous path primitives recorded by the user. The display also reflects changes in the robot's commanded position as dictated by forces applied to the end effector that are processed by the impedance control subsystem. This functionality provides for operation for the PFMA's digital control system when either the analog-I/O system is in a state of maintenance and repair or when "safe" debugging of new controller algorithms is necessary. The ability to execute autonomous task primitive motions in this manner ensures that when these segments are executed using the PFMA they will complete their intended operation.

2.2 Control System Upgrades

2.2.1 Robot Servo Command Input Upgrades

During the IRSS phase II effort joint performance data was collected for the PFMA and analyzed in an effort to improve joint disturbance response characteristics. The difficulty with which this was accomplished illustrated the need to provide utilities within the IRSS robot controller to manually inject various wave forms directly into the joint controllers of the robot for the purpose of analysis and diagnostics. During IRSS phase IV this capability was implemented providing the ability to inject sine and square wave functions into the forward path of each of the robot's independent joint controllers. Using this facility and a user defined configuration menu, the amplitude, frequency and relative phase of these references for each of the robot's joints is user configurable.

2.2.2 Data Recording and Analysis Upgrades

To perform human factors experiments during phase IV of the IRSS contract the addition of a data recording capability was implemented and integrated into the robot controller. Because important feedback information is distributed throughout the robot control system, fundamental components of the recording facilities must function as a unit across multiple processors each with the ability to perform independent data recording. To meet these requirements, a set of software modules was built around a common data structure and set of low level software utilities, each capable of functioning independently on an isolated processing node (Figure 2-2).

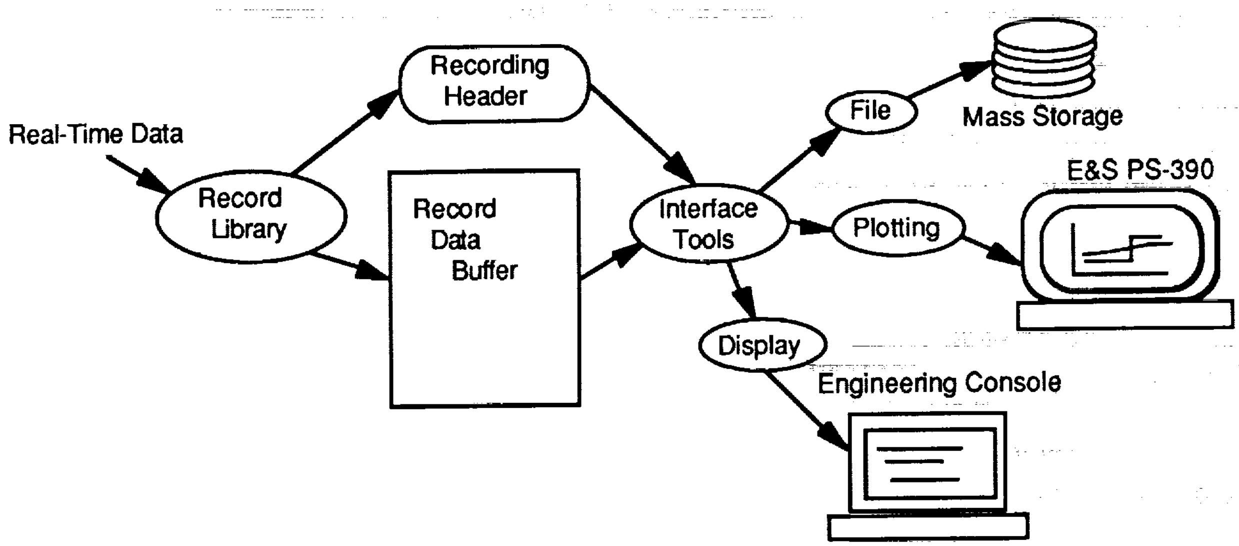

Figure 2-2. Distributed Data Recording and Display

The data recording capability has several primary components; raw recording, raw display, transfer to mass storage and graphics display for analysis purposes. The raw data recording facility permits the user to select data to be recorded, its recording rate, its recording mode and the amount of memory used to record the particular data item. A selection from over 15 different data items is currently provided. Start, stop and reset of data recording is controlled from the main engineering console terminal. Using the data display utility the user can scroll through recorded data, stopping it as necessary to examine individual items. To quickly examine the recorded data a graphics support system is provided that scales and passed the recorded data (via RS-232) to the Evans & Sutherland PS-390 graphics computer. On the PS-390 display a plot is produced complete with grid marks, title, axis labels and a legend in full color. Up to five overlaid plots can be produced making comparison of system performances fast and efficient. The user has complete control over nearly all aspects of the plot produced. Permanent storage of recorded data is accomplished by translating binary values to ASCII and then saving them in user defined files on the Heurikon hard disk. From this disk they can be transferred to other remote systems using either streaming tape or floppy. Currently, there is approximately 400K of memory available for use with data recording. Filling all of this memory with data produces an output disk file which when saved is nearly 1 megabyte in length.

2.2.3 Software and Hardware Problems Addressed

In the course of performing phase IV work a variety of software problems were identified and corrected. These included problems associated with sometimes unreliable power-up and down of the system and structure of the system world model. To provide support for the serial interface to the VPL data glove an additional MVME-410 quad serial card was added to the I/O chassis. Due to the large amount of serial data processed by the I/O computer, this addition precipitated the need to convert I/O chassis hardware and software operating the serial interface from a poling method to an interrupt driven scheme. This upgrade not only incorporated the data glove hand controller but also improved the reliability and speed of the Lord Force/Torque sensor interface. Documentation of existing and newly developed system software was improved to help clarify system operations and data flows.

Despite the fact gains in system reliability have been made during the phase IV effort, there do remain several significant problems with the system. The first of these problems has to do with the interaction of the system I/O chassis and the Polhemus emitter functioning with the VPL data glove. Because of electrical noise induced by fluctuating magnetic fields coming from the emitter, the I/O chassis will occasionally receive spurious signals while attempting to access the VME bus. This typically results in a failure indication, "crashing" the system. Improved shielding of the I/O chassis backplane would be the most obvious solution to this problem. A second problem is that one of the Heurikon V2F real-time computational processor cards occasionally fails indicating a memory parity error. The suspected cause in this case is that the

VRTX kernel software which performs multi- tasking on the board was not saving and restoring floating point coprocessor registers when appropriate. A simple upgrade of VRTX software from version V20 to V32 should eliminate this difficulty. With these problems data collection during the experimental phase of the phase IV effort was hampered, requiring an excessive amount of individual data file processing to occur before the information could be analyzed.

2.3 System Simulation Capabilities

2.3.1 Simulation of Limited Bandwidth Communications Link

The design and preliminary implementation of a limited bandwidth, bidirectional data link was accomplished during phase IV of the IRSS contract. The objective of this task was to examine the effects of extremely limited data communications rates upon teleoperation, system safety and system controllability of a robotic system whose operator and user interface are separated from the real-time control system and robot. In total, it was anticipated that this system would emulate an Earth base control station for an on-orbit remote manipulator such as the Orbital Maneuvering Vehicle (OMV), the Flight Robotic Servicer (FTS), or the Satellite Servicing System.

The bandwidths selected for this system were roughly equivalent to that which were expected for the proposed OMV. The uplink data rate from the control station is designed to be user configurable ranging from 230 to 810 bits/second. Uplink data packet sizes range from 23-27 bits/packet with transmission rates of between 10 and 30 packets/second as selected by the user. In the preliminary design, the downlink bandwidth was significantly greater than that of the uplink, ranging from 2300 to 6900 bits/second with packet sizes of 230 bits/packet at rates from between 10 to 30 packets/second. Time delays for packets are user configurable ranging from 0 to 5 seconds each direction.

A strategic method for optimizing system data integrity between the various components of the distributed control system was developed. The goals of the methodology developed was to optimize the data flow through the constrained link by eliminating the transfer of redundant information and providing a criticality prioritized scheduling framework for the transmission of system data. On the uplink side, the ability to perform robust teleoperation of the manipulator across the data link was desired. A block diagram detailing the organization of this system is shown in Figure 2-3. A description of the major components found in the system is provided below.

2.3.1.1 Delay Blocks

These blocks emulate a realistic time delay anticipated between the Earth based ground station and a remote robotic servicer. Delays are user selectable and can range from 0 to 5 seconds.

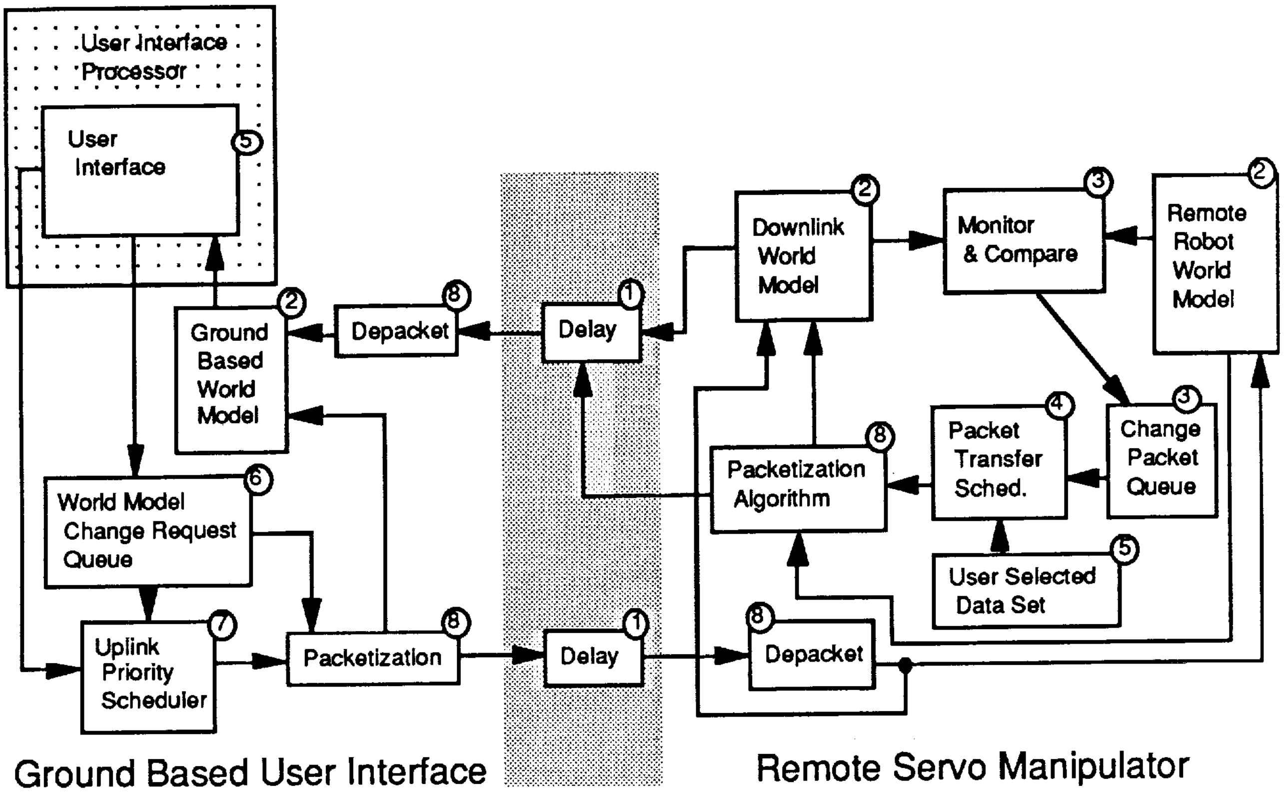

Figure 2-3. Reduced Bandwidth Communications Link Simulation

2.3.1.2 World Models

Within this system there are three separate world model entities. The first is the Remote Robot World Model. This world model is the true informational data base from which the real-time operations of the robot occurs. The system real-time computational and I/O processors update this world model causing tasking data to flow in the remote controller. The second world model is the Downlink World Model maintained by the monitor and compare function on the remote robot control system. The monitor and compare subsystem compares data within the Remote Robot World Model (the true world model) to this local model and generates a list of discrepancies between the two. The Downlink World Model is intended to be a duplicate of what is the third world model, namely, the Ground Based World Model. The Ground Based World Model is the only record that the remote operator interface has for determining the operational state of the remote manipulator servicing system.

2.3.1.3 Remote Monitor & Compare

The remote monitor and compare function is used to help the Ground Base World Model reflect as accurately as possible the state of the Remote Robot World Model. This function is constantly comparing its local world model with the Remote Robot World Model identifying items which differ. Differences between the two indicate that the Ground Based World Model does not accurately reflect the true state of the Remote Robot World Model and so transmission of this discrepancy is necessary. This function helps ensure that packet bandwidth is not wasted transferring data to the ground station that currently reflects the existing state of the remote world model. Output from this function is a list of world model data items requiring update on the Ground Based World Model. This list of data items in need of transfer is maintained and managed in a queue.

2.3.1.4 Packet Transfer Scheduler

The packet transfer scheduler is the mechanism which at the downlink transmission rate determines the contents of each successive downlink packet. Fundamental definition of the data scheduled for downlink transfer is determined by the user (see the discussion of the User Interface in this section). Normally, for any given transmission frame the user will have identified the particular piece of data to be transferred via the downlink. In "spare frames" where this is not explicitly dictated, the Packet Transfer Scheduler goes to the head of the Change Packet Queue and removes the highest priority item, preparing it for transfer. With each world model data item possessing its own relative criticality level (thus providing a rough measure of its importance), transfer priority of items in the Change Packet Queue can be assessed. In the current implementation the position of a data item in the downlink transmission queue is determined by a combination of how long the item has been in the transfer queue, and its relative criticality. In some cases a data item of low criticality may be transferred ahead of another data item which possess a higher criticality because it has been in the transfer queue significantly longer. This queueing approach guarantees that data items which have relatively low criticality do not starve (e.g. they are never transferred), but that data items which have greater significance are more rapidly updated as they change.

2.3.1.5 User Interface

Through the user interface, configuration of the remote link simulation is controlled. For the definition of the uplink a menu is used to set the packet transfer rate, the packet size (in bits), the time delay and encoding method used to transfer remote control data. Operation of the remote system simulator can also be enabled and disable from this menu. A second menu to control the downlink permits the user to set the downlink packet rate and to explicitly configure the transmission rate of the following world model data items:

- Robot Commanded Position
- Commanded Joint Positions
- Joint Voltage Commands & Motor Tachometer Impedance Offset
- End Effector Forces
- World Forces

- Actual Joint Positions.
- System State Variables
- General System Data that is Changing

As the remote link simulation is enabled and disabled, communications tools used with the world models redirect access appropriately between the Ground Base World Model and the Remote Robot World Model. The fact that this is occurring remains totally transparent to the modules accessing world model data items. This greatly enhances the ability to debug the system allowing the user to browse multiple world models as needed.

2.3.1.6 World Model Change Request Queue

On the ground based user interface side of the remote link, commands and change requests coming from the user interface are queued before they can be transferred to the remote system. Requests wait in this queue until they are packetized and sent. Once a data item has been packetized and is passing through the delay subsystem, the new state of this world model data item is reflected in the Ground Based World Model. On the remote manipulator side of the link, whenever a packet is received both the Downlink and the Remote Robot World Model are updated to reflect the new state of the system. If the particular data item updated is found in the downlink packet queue (ready for downlink transmission) it is then removed.

2.3.1.7 Uplink Priority Scheduler

The Uplink Priority Scheduler is used to determine the relative sequence of packets which are transferred from the user interface/ground station simulator to the remote manipulator. A simple priority based scheduling algorithm is used, preempting any stream of direct remote command packets with any other command type being issued from the user interface. Since typically the number of commands coming from the user interface directed to the real-time controller is small, a First In, First Out (FIFO) queue is used to hold pending commands. When no pending user interface uplink control commands are available for transmission, the uplink continues to transfer remote direct command packets according to the mode of operation (Cartesian servo, joint servo or teleoperation) of the ground based system.

2.3.1.8 Packetization/Depacketization

For the data being transferred to and from the remote manipulator packetization and depacketization is necessary. Within the system, uplink packaging is much more sophisticated that that for downlink data due to the narrower bandwidth of the uplink side. Before transmission, command information must be compressed if robust teleoperation is to be possible. A discussion of these compression techniques is provided in the following paragraphs.

There are currently three specialized modes of transfer which are used to directly control the motion of the remote manipulator. These three modes are the transmission of an absolute robot commanded position, the transmission of a Cartesian delta (typically associated with a hand controller), and the transmission of absolute robot joint commands. In each case it is taken for granted that six degrees of freedom (DOF) of information is to be transferred. In each case real numbers are normalized and scaled across some metric of the robot world environment (maximum positions for Cartesian workspace or joint angle or maximum delta respectively). This reduces the storage and transmission requirements for the data without unduly diminishing its accuracy.

For the direct remote command of the manipulator (this implies direct transmission of Cartesian or joint absolute positions or deltas) there are currently four encoding methods proposed for data transfer. The first and most simplistic of these transfer schemes is the Standard Transfer packet method (Figure 2-4). This type of packet is comprised of a more bit (indicating that the packet is just one more in a continuous stream), a 2 bit DOF selector field followed by 2 individual data fields containing the command data for the robot. When the packet type is a robot Cartesian reference command the data fields contain normalized integer representations of either X and Y, Z and Yaw, or Pitch and Roll Cartesian commanded positions. The degree of freedom selector field indicates which of these coordinate pairs is present in a given packet. As the length of these packets range from 23 to 27 bits, additional bits are successively added to each of the data fields in a left first, then right, then left again fashion. When uplink packets are sized at 23 bits each field is 10 bits in length. When the packet size is 27 bits each data field contains 12 bits. When hand controller delta commands are being processed the data fields hold X & Y deltas, Z delta and Q1 of a quaternion, or Q2 and Q3 of a quaternion (Note that given Q1, Q2, and Q3, Q4 can be determined by normalizing the quaternion vector; this is safe for delta transmissions but is undesirable for transmission of commanded Cartesian orientations because of relatively large errors associated with discretization). In the case of the joint reference command packet, base and shoulder, elbow and first wrist, or second wrist and third wrist commanded joint position data is scaled and encoded.

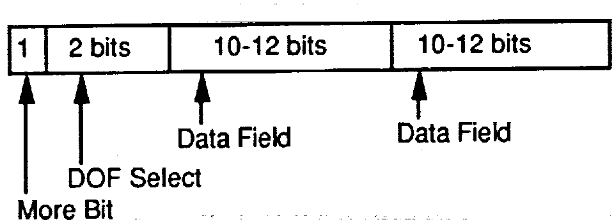

Figure 2-4. Uplink Data Compression: Standard Transfer Packet

The second encoding scheme used for the direct remote command uplink was the high resolution sliding scale methodology (Figure 2-5). This technique provides three data fields in each packet as opposed to two (as in the Standard Transfer packet). In this case, only 1 bit to select the DOF is needed (assuming uplink data will never have more than 6 degrees of freedom). This packet type differs from the Standard Transfer packet in that in addition to the third data field a multiplier field also exists. This multiplier dictates the number of left bit shifts that the data found in the 3 data fields must be subjected to before they are embedded into output data. In 23 bit packets this is a 3 bit field (providing an 8X multiplier), and in all larger packets it is 4 bits (providing a 16X multiplier). As additional bits are successively added to the packet size they are evenly distributed among the data fields left to right. When Cartesian robot reference command packets are provided they contain either X,Y and Z, or yaw, pitch and yaw commanded position components within the data fields. Similarly, hand controller delta packets will contain either X,Y and Z scaled deltas or Q1,Q2 and Q3 scaled quaternion values. Finally, joint reference command packets will provide either scaled base yaw, shoulder pitch and elbow pitch commands or scaled first wrist, second wrist and third wrist commands. Note that using this multiplier a higher resolution of robot commands can be maintained than is possible with Standard Transfer packets.

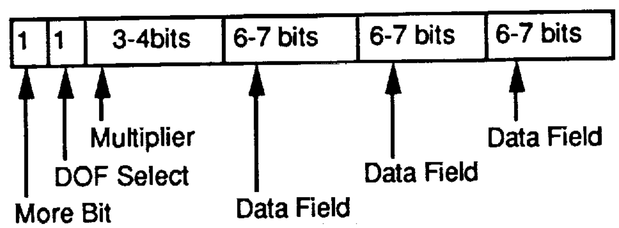

Figure 2-5. Uplink Data Compression: High Resolution Sliding Scale Packet

The third encoding method, referred to as the High Speed Sliding Scale encryption scheme, is comprised of one data packet with data for all six DOF of the robot (Figure 2-6). Each data field is either 3 or 4 bit of differential data for each DOF (note that because all are differential transmissions this is different from other packet types). A scale field of 2 bits provides a shift multiplier to be applied to each of these data fields before they are combined with existing data to form an output command. Commanded Cartesian reference delta packets contain the X, Y, Z and yaw, pitch, yaw differentials successively. Hand controller differentials are transferred as X, Y, and Z deltas followed by Q1, Q2, Q3 quaternion differential components. Commanded joint angle data ordering follows the robot's sequential joint structure from shoulder yaw to the third wrist.

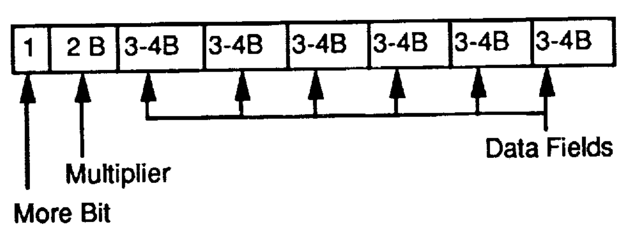

Figure 2-6. Uplink Data Compression: High Speed Sliding Scale Packet

The fourth direct command encoding scheme is called the Modified Sliding Scale (Figure 2-7). This method is very similar to the High Resolution Sliding Scale method and the Standard Transfer technique. This method contains two separate data fields each with a separate DOF selector field. The encoding method of a shift multiplier followed by a scaled integer value for the particular degree of freedom is synonymous with the technique use in the High Resolution Sliding Scale method. The contents of the data packets (as normalized integer values and their order) are also equivalent. An advantage offered by this encoding method is that information for two independent degrees of freedom can be transferred in one packet, each with its own shift multiplier which can optimize the position of the data in the data field in the packet. A technique such as is in floating point math where an implied bit is found to the left of the mantissa could be applied here to increase the information transferred in each packet.

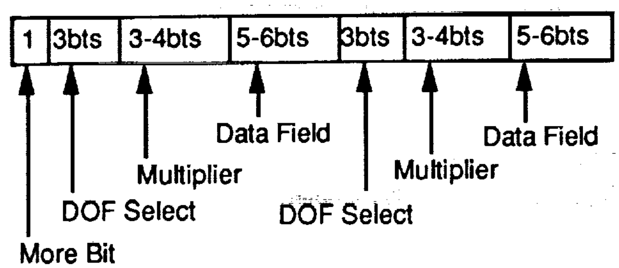

Figure 2-7. Uplink Data Compression: Modified Sliding Scale Packet

Each of these encoding schemes has its relative advantages and disadvantages. The Standard Transfer packet is simple to encode and decode, but requires a minimum of three packets to form a complete 6 DOF command. Another disadvantage of the standard transfer scheme is that the smaller the size of the data packet, the less resolution the data in the packet has. With only two packets the High Resolution Sliding Scale packet can form a complete command (a 33% improvement over the Standard Transfer), however, significant bits may be lost when actual commanded positions are being transferred requiring the system to wait for transmission of lower order bits before a truly complete command is received. Although in the case of absolute position commands this can pose a problem, transmission of delta in this fashion can be very efficient (because differential information can be scaled to minimize use of the upper bits in a value). The High Speed Sliding Scale algorithm can encode a complete command in only 1 packet but can only be used in a differential transmission mode, not in an absolute command mode. Also, because each data field is so small, there is always a tradeoff between bandwidth of motion and quantization errors. The Modified Sliding Scale method combines the advantages of the High Resolution Sliding Scale with the flexibility of being able to select independent degrees of freedom concurrently. Its disadvantage is that it can have a lower bandwidth than the Standard Transfer scheme if all robot degrees of freedom are changing rapidly.

Downlink packaging is much simpler, with each packet containing 230 bits. These bits are divided into 18 individual fields (see Figure 2-8). The right most components are comprised of fourteen 16 bit data fields. These data fields are filled with raw data dumped into them in a left field first fashion. No specialized compression goes on. This permits the transfer of up to seven 32 bit reals, fourteen 16 bit integers or twenty-eight characters per packet. The left most bit in the packet (the more bit) indicates whether the packet is a continuation in a stream of packets, and the power-up bit indicates whether the remote manipulator is actively powered up. An error bit is set to indicate that the robot is currently in an error state and a mode field is used to indicate information about the current configuration and state of the uplink. Predefined packet sequencing and synchronization is assumed on both ends of the data link. This reduces overhead and increases system bandwidth by permitting multiplexing of data through the manipulator to ground station link.

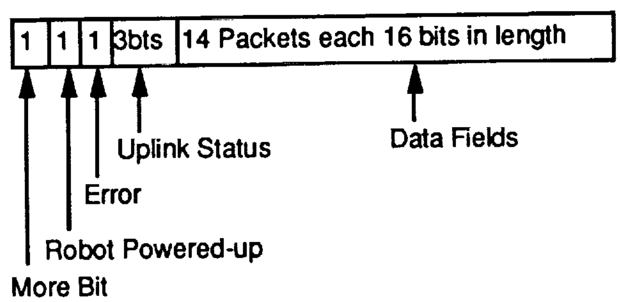

Figure 2-8. Downlink Data Compression Packet Format

To fully implement the narrow bandwidth remote link simulation system described here additional processing capability had to be added to the Heurikon/IRSS computational chassis. Selected was a single Heurikon V2F processor card much like those already performing real-time calculations in the computational chassis. The only difference between this processor card and others in the same chassis is that the new processor card has 4 megabytes of on-board memory as opposed to 1 megabyte. In a hardware/software interaction sense, Figure 2-9 contrasts the phase II world model to user interface communications method to that implied in this discussion. As can be seen, the additional processing capability simply acts as the link between the user interface and the real-time robot control/servo system.

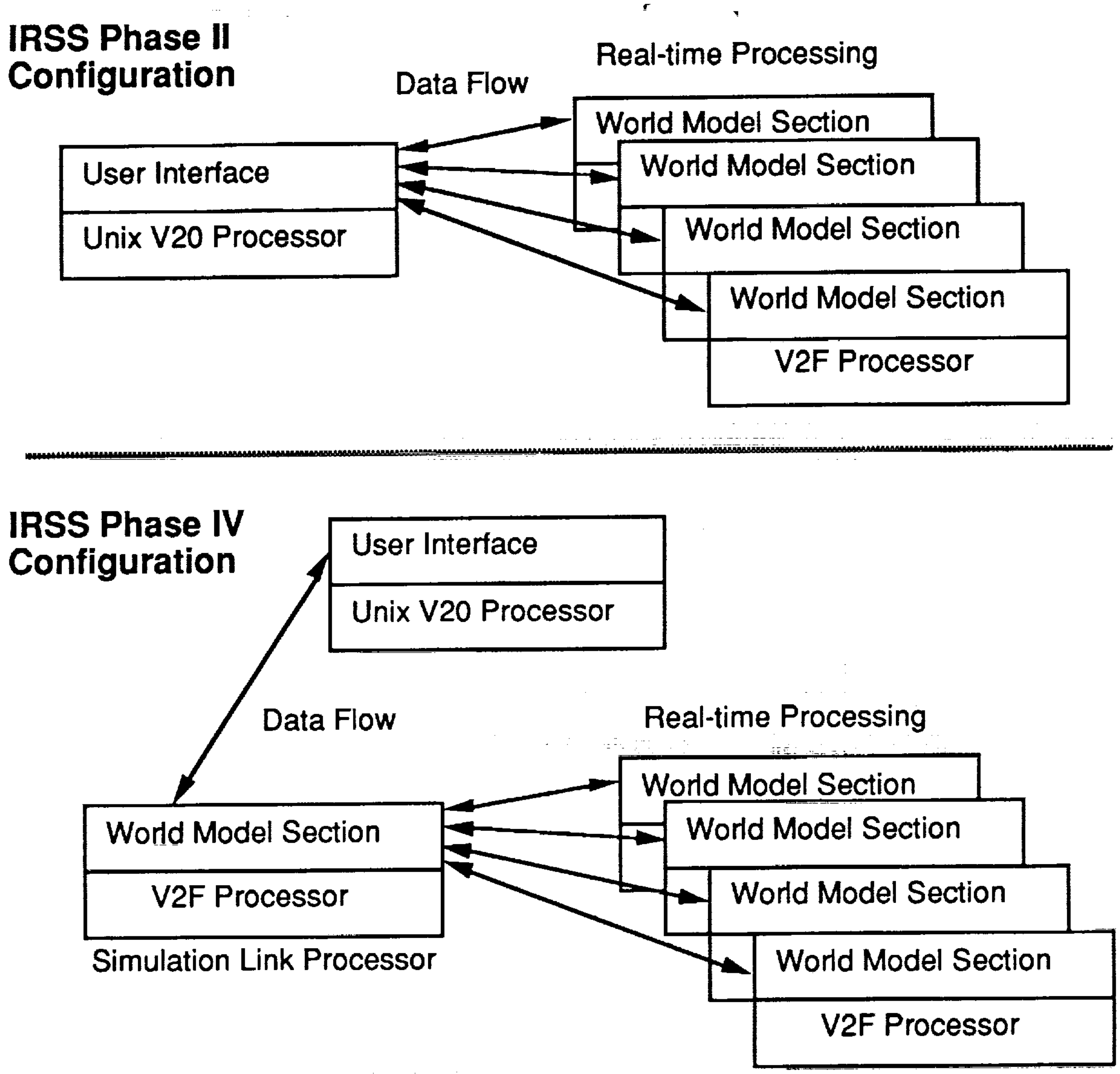

Figure 2-9. Data Flow Comparison for Phases II and IV

In summary, the system designed for the simulation and control of a remote manipulator provides a realistic and practical approach to overcoming problems associated with a limited bandwidth link with variable time delay. Although every aspect of the proposed design was not fully realized in the phase IV effort, a foundation has been established upon which further enhancements can build. It is expected that results coming from this implementation and the study of such, could have significant impact upon the assessment and feasibility of performing many satellite servicing tasks from a ground base control station. With the flexibility that this system provides in terms of data rates and packet sizes, a variety of comparison and performance studies could be performed that evaluate packet encoding methodologies versus user response bandwidth. In the long term, methodologies for swapping of encryption techniques as a function of the operational motion may need to be considered.

2.3.2 Off-line Simulation Capabilities

To provide the capability to develop software for the IRSS system independently from the PFMA and related hardware, a non-real time system simulator has been gradually developed and upgraded through phase II and phase IV of this contract. This simulator permits an IBM-PC to be used as a hardware platform on which real-time software can be debugged, evaluated, modified and enhanced. Using this development environment approximately 85% of the software modules which are used in the real-time control of the PFMA are linked directly (without source code changes) to simulation software utilities. Operating on a PC, a large variety of tools are available for debug, configuration management and graphics. Because the simulation is non-real time, relative synchronization of tasks and system data flows can be examined at various levels of detail.

At the heart of this simulation is software that emulates the VRTX multi-tasking kernel found on each of the Heurikon V2F real-time computational processor cards. This kernel maintains records of which system tasks are active and executes them according to their relative priority and availability. The full IRSS system user interface executes concurrently with the real-time simulation allowing the user to monitor system parameters and inject new commands and disturbances into the system. A standard plant joint model is used to emulate independent joint dynamics for all six degrees of freedom of the robot. With the modular nature of these plant models as well as the various joint controllers this system can be used to simulate robots other than the PFMA and design joint controllers for such.

Without hand controllers, touch screens or the PS-390 interfaced to the PC, operation of the simulation via teleoperation, touch, and graphics is not currently provided although these capabilities could be added. Due largely to the fact that portability of system software has recently been considered, porting of this simulation to a Unix based workstation or mainframe computer could be performed to increase the system's speed of execution and its capabilities. Currently, continued enhancements of the IRSS control system are being performed using the PC.

3.0 Teleoperation Performance Study

3.1 Introduction

This study evaluated three issues related to remote control of robotic systems. These three issues were the control reference frame, impedance level, and amount of time delay present in the system. The effect of different levels of these parameters on operator performance was determined.

3.1.1 Reference Frame

Reference frame refers to the location and orientation of the axis of control. The reference frame can be fixed in space or can be located with respect to a moving point (object) in space. An example of a reference frame fixed in space would be a reference frame coincident with a fixed camera or fixed portion of the robot, for example the shoulder. With a fixed reference frame, the axes would remain fixed regardless of the orientation of the robot gripper. For example, +Z would always point up from the base of the robot (even if the gripper was rolled 90-degrees such that it was looking upside down). An example of a reference frame not fixed in space would be one coincident with the gripper or a gripper mounted camera on the manipulator. In this case, the reference frame changes to correspond to the orientation of the gripper (or gripper mounted camera). For example, +Z would always be up from the gripper (as opposed to up in fixed space). The selection of the location of the reference frame and whether or not the reference frame is fixed in free space or fixed with respect to a moving object is based on many considerations such as the type of task being performed, size of the workspace, and feedback being provided to the operator.

3.1.2 Impedance

Impedance refers to the apparent stiffness and damping of the manipulator at the end effector. Impedance control laws allow compliance to be programmed, reducing the forces resulting from environmental contact. In Cartesian space, end effector forces measured by the wrist-mounted force/torque sensor can be utilized to modify the effective impedance of the end effector using position-based impedance control. A stiff manipulator exerts large forces on the environment during contact in response to small commanded motions. This can result in physical damage to the contacting parts. A soft manipulator yields when in contact, resulting in smaller interaction forces. If the impedance control is too soft however, the task may be difficult or impossible.

3.1.3 Time Delay

One of the problems that arise in remote control of robotic systems is the introduction of time delays in the transmission of commands from the operator to the robot and feedback from the robot to the operator. Delays on the order of 2 to 4 seconds are reasonable for ground control of space robotic systems.[2] Studies have shown that operator performance is affected negatively by the introduction of time delay for such tasks as fine precision peg-in-the-hole[3] and pursuit tracking,[4] and that operators adopt a move-and-wait strategy.[5]

3.2 Research Methodology

This study was conducted at the Marshall Space Flight Center (MSFC) in the Robotics Laboratory. The operators controlled the Proto-Flight Manipulator Arm (PFMA) to perform a simulated Orbital Replacement Unit (ORU) replacement task.

3.2.1 Apparatus

Figures 3-1 and 3-2 show the layout of the various components used in this study. Two task panels were used and each had an ORU receptacle. Contact switches were mounted on the rear face of the receptacles to detect when the ORU was completely inserted. Feedback of successful insertion of the ORU was provided to the operators by the illumination of an Light Emitting Diode (LED) located above each ORU receptacle. Two infrared photo-interruptor sensors were placed on standoffs of approximately 1.5 inches in front of each panel to indicate when the ORU was near the front face of the panel and receptacle (Figure 3-3). This sensor information was used to signal the transition between the slewing and fine alignment task segments. For example, Task Panel (TP) #1 Insertion subtask started when the ORU was sensed by the sensor on the standoff and ended when the sensor on the rear face indicated that the ORU was completely inserted.

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[2]Buzan, F. T. and Sheridan, T, B. (1989, November). A model-based predictive operator aid for telemanipulators with time delay. In *Proceedings of the 1989 IEEE International Conference on Systems, Man, and Cybernetics.* November 14-17, 1989. Cambridge, MA. NY: IEEE.

[3]Hannaford, B. and Kim, W. S. (19, November). Force reflection, shared control, and time delay in telemanipulation. In *Proceedings of the 1989 IEEE International Conference on Systems, Man, and Cybernetics.* November 14-17, 1989. Cambridge, MA. NY: IEEE.

[4]McCormack, L. B., Detroit, M. J., and See, D. N. (1987, May). Improving pilot-vehicle integration using cockpit display dynamics. In *Proceedings of the IEEE 1987 National Aerospace and Electronics Conference NAECON.* May 18-22, 1987. Vol. 2. NY: IEEE.

[5]Ferrell, W. R. (1965). Remote manipulation with transmission delay. *IEEE Transactions on Human Factors in Electronics,* HFE-6 (pp. 24-32). Cambridge, MA: IEEE.

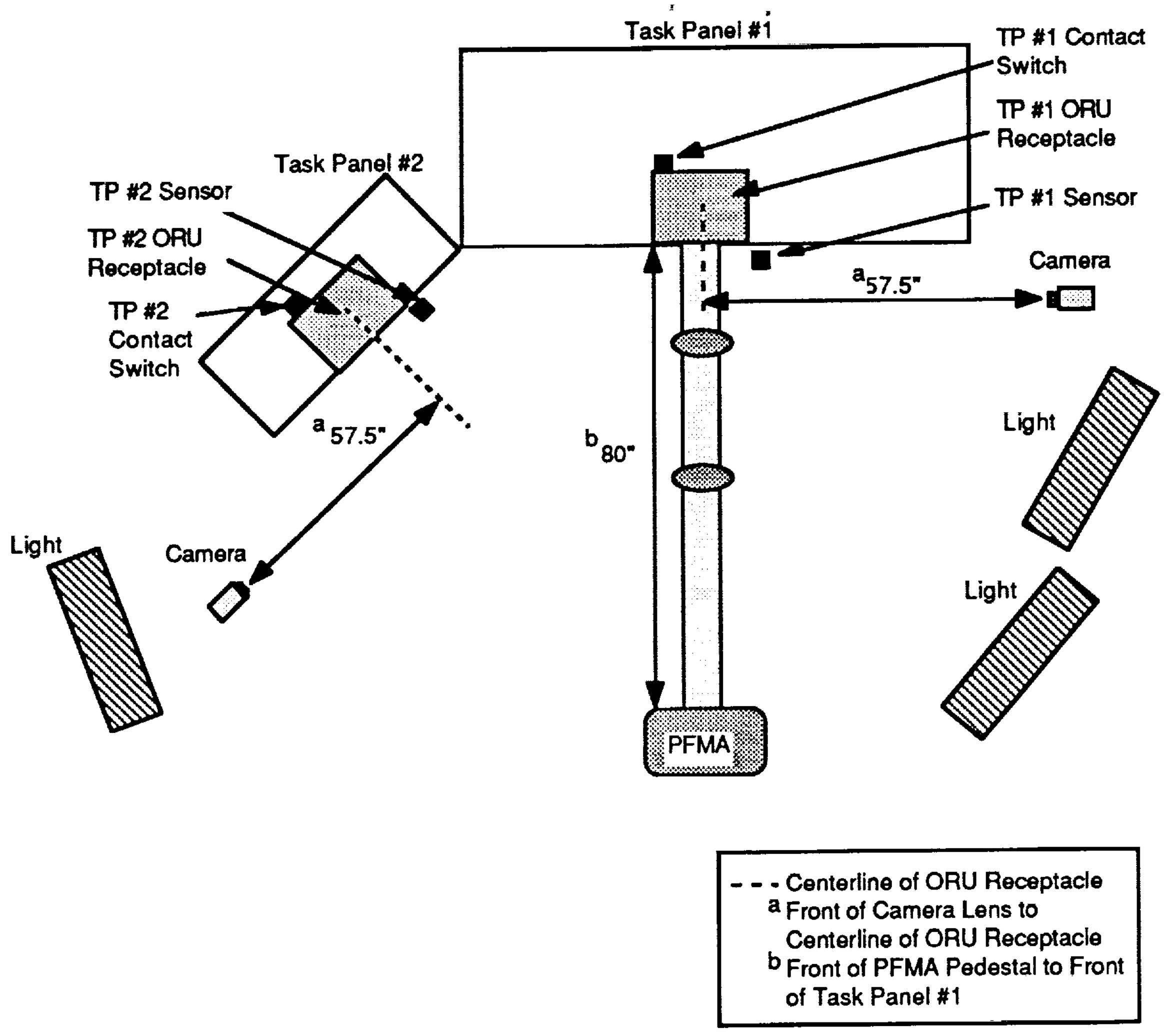

Figure 3-1. Top View of Worksite.

The operators controlled the PFMA via a 6-degree of freedom (DOF), rate CAE hand controller located at the workstation (Figure 3-4). The CAE hand controller fits in the palm of the operator's hand and has an activation switch located at the index finger, which must be fully depressed to issues commands to the PFMA. The workstation has three-bays and is configured like the console currently envisioned for the Orbital Maneuvering Vehicle (OMV). Partitions were placed between the operator and PFMA such that the operator could not see the worksite directly. Two black and white camera views of the worksite were presented on the console monitors.

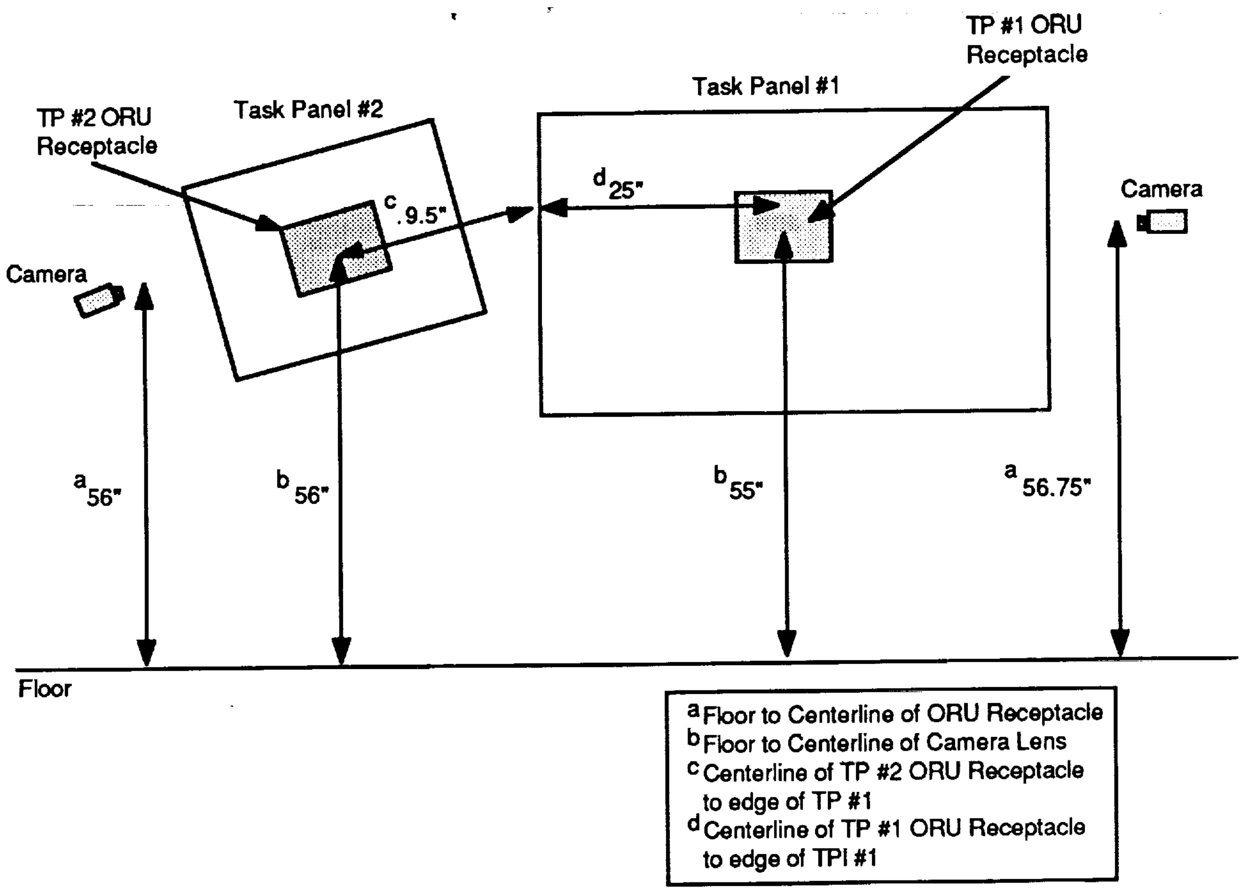

Figure 3-2. Front View of Worksite.

3.2.2 Task

The task simulated the major elements of an ORU replacement task. This task required the subjects to remove the ORU from TP #1 receptacle, slew to TP #2, insert it into TP #2 receptacle, remove it from TP #2 receptacle, slew back to TP #1, and insert it into TP #1 receptacle (refer to Figures 3-1 and 3-2). The subjects received feedback when the ORU was inserted fully via an LED located above each ORU receptacle. The task contained two distinct components—large, non-environmental contact slewing motions, and fine alignment and positioning motions.

3.2.3 Subjects

Twelve students from the University of Alabama at Huntsville participated in this study. Six of the subjects were male and 6 were female. The subjects were paid $10.00 per hour for their participation. None of the subjects were familiar with the experimental task, hand controller, or manipulator used in this study.

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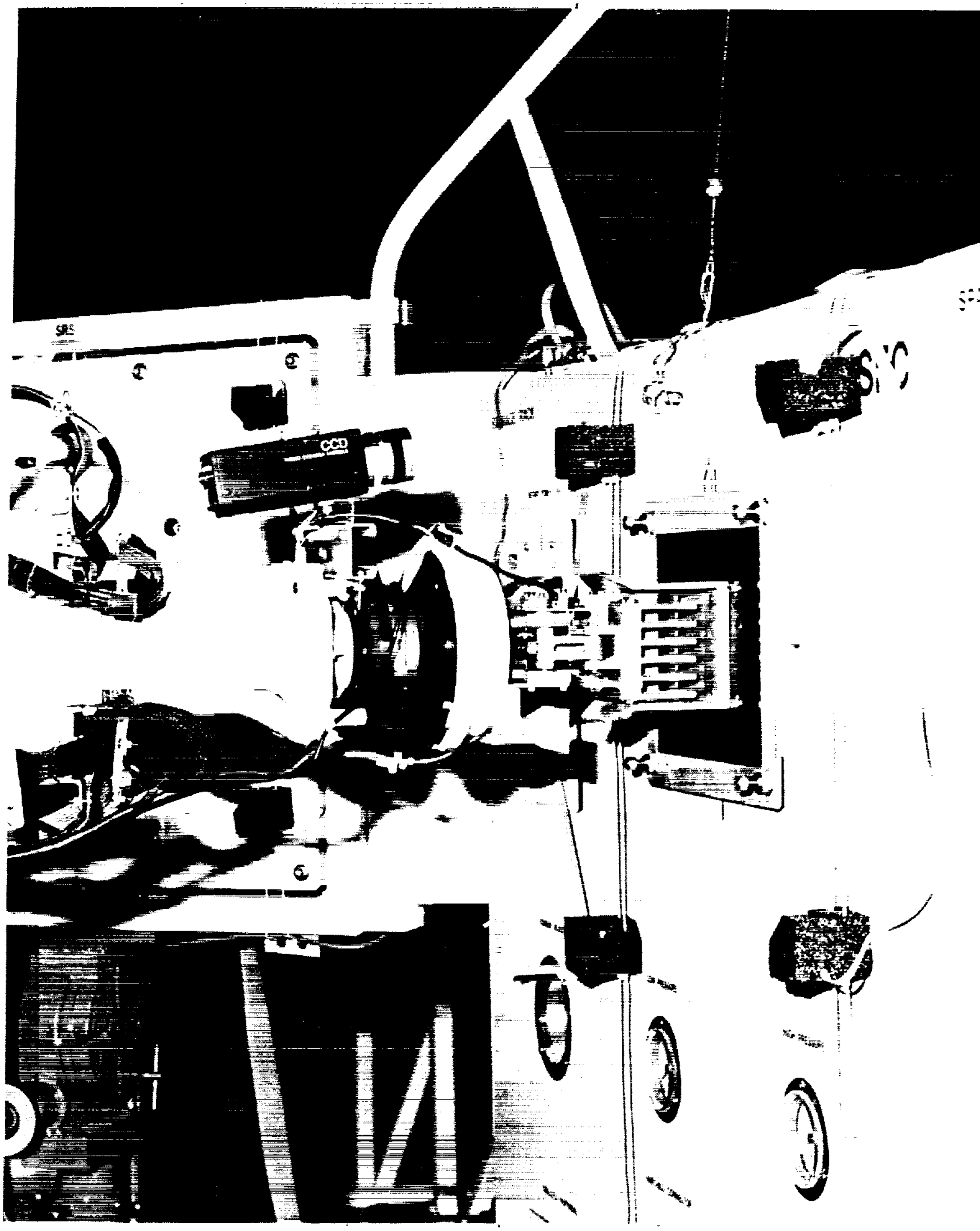

Figure 3-3. Photograph of Manipulator and Task Panels with Sensors

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Figure 3-4. Photograph of Subject at Operator Workstation.

3.2.4 Procedure

The subjects attended a training session during which they were informed of the experimental setup, including information on the operation of the PFMA, hand controller, and location of cameras. The subjects were informed of their rights as study participants, signed an Informed Consent Form (located in Appendix A), and filled out a background questionnaire (located in Appendix B). The task was explained to the subjects and demonstrated by the test monitor. The operators were trained on the system by performing six training runs that were performed in the following order:

- End Effector Reference Frame, Stiff Impedance, No Time Delay
- End Effector Reference Frame, Soft Impedance, No Time Delay
- World Reference Frame, Stiff Impedance, No Time Delay
- End Effector Reference Frame, Stiff Impedance, 1 Second Time Delay
- End Effector Reference Frame, Stiff Impedance, 2 Seconds Time Delay

The first training run was viewed as the baseline condition and was run twice. In the four remaining runs, one parameter changed from the baseline. The operators were informed of the changes between training runs so that they could better understand the differences observed in system performance.

In addition to the two camera views provided on the control console, the subjects were allowed to view the task directly and were provided with a graphic simulation of the manipulator during the training session. The subjects were aware that the direct view of the task and graphic display would not be available during the experiment. The participants were told that it was more important to concentrate on performing the task well, as opposed to performing it fast.

At the beginning of each set of data collection runs, the subjects were given a practice run with the baseline condition. Prior to each data collection run, the participants were told the reference frame condition for that run, but were not told the impedance or time delay conditions. At the completion of each experimental run, the participants provided the test monitor with a Cooper-Harper (C-H)[6] rating of the task difficulty (rating scale is located in Appendix C). After the completion of all 12 experimental runs, the subjects completed a post-test questionnaire (located in Appendix D). Experimental runs that could not be completed within 10 minutes were stopped and were recorded as incomplete. Complete task segments from incomplete (discontinued) runs were included in the analysis.

3.2.5 Experimental Design

A within-subjects design was used, such that all of the subjects experienced all of the experimental conditions. A fully counterbalanced presentation order was used, meaning that no two subjects experienced the experimental conditions in the same order.

3.2.5.1 Independent Variables

Reference frame control mode, time delay, and impedance level were evaluated in this experiment.

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[6]Wierwille, W. W. and Casali, J. G. (1983). A validated rating scale for global mental workload measurement applications. In *Proceedings of the Human Factors Society—27th Annual Meeting.* October 10-14, 1983. Norfolk, VA. Vol. 1, pp 129-133. Santa Monica, CA: HFS.

Reference Frame Control Mode – This study evaluated two reference frame control modes—a World and an End Effector frame of reference. The world reference frame was located at the point of intersection of the PFMA shoulder pitch and shoulder yaw. This control mode mapped hand controller motion relative to a fixed coordinate system in space, regardless of the orientation of the end effector. The end effector reference frame was located at the center of the gripper and its coordinate system varied in space relative to the orientation of the end effector. For example, in the World Reference Frame condition, the +X direction was always pointing towards Task Panel #1. In the End Effector Reference Frame, +X was always pointing out of the end of the gripper, regardless of the orientation of the gripper. When the end effector and world frames were aligned, such as when the ORU was inserted into Task Panel #1 receptacle, these two control modes were the same. However, when the two frames were not aligned, such as when inserting the ORU into Task Panel #2 receptacle, the control modes were different.

Impedance – Two levels of impedance were evaluated. The first level was referred to as "stiff" and consisted of the following stiffness and damping values:

Stiffness:	$k_x = 2$	$\mathbf{k_y = 2}$	$k_z = 2$	$k_{ox}, k_{oy}, k_{oz} = 20$
Damping:	$b_x = 10$	$b_y = 10$	$b_z = 10$	$b_{ox}, b_{oy}, b_{oz} = 100$

The second level was referred to as "soft" and consisted of the following stiffness and damping values:

Stiffness:	$k_x = 2$	$\mathbf{k_y = 10}$	$k_z = 2$	$k_{ox}, k_{oy}, k_{oz} = 20$
Damping:	$b_x = 10$	$b_y = 10$	$b_z = 10$	$b_{ox}, b_{oy}, b_{oz} = 100$

The parameter and value that differed between the two conditions is noted in bold.

Time Delay – The three levels of time delay that were evaluated were no time delay, 1 second time delay, and 2 seconds of time delay.

3.2.5.2 Dependent Variables

Several objective performance measures were collected, including the amount of time required to perform the task, successfulness of inserting the ORU in the receptacle properly, and forces and torques at the end effector during insertion. The ORU insertion success was based on whether or not the subjects fully inserted the ORU into the ORU receptacle. This was determined by sensing the contact switch mounted on the back surface of each ORU receptacle. Additionally, a C-H rating was collected after each experimental run to provide a subjective assessment of task difficulty.

3.3 Data Results

Pearson's (r) correlations were calculated between the dependent variables and it was determined that the appropriate dependent measures for analysis purposes were TP #1 and #2 Insertion Success rate, total time to complete the task (Task Duration), Cooper-Harper rating of task difficulty, and the root mean square (RMS) Forces and

Torques at the gripper for TP #1 and #2 Insertion. Correlations between these dependent variables are located in Table 3-1.

Table 3-1. Correlation Matrix for Dependent Variables.

Dependent Variables	Cooper Harper Rating	Task Duration	TP #1 Insertion Success	TP #2 Insertion Success	TP #1 Insertion RMS Forces	TP #2 Insertion RMS Forces	TP #1 Insertion RMS Torques
Task Duration	0.634*						
TP #1 Insertion Success	-0.003	-0.076					
TP #2 Insertion Success	-0.158	-0.062	-0.026				
TP #1 Insertion RMS Forces	0.130	0.079	-0.090	0.092			
TP #2 Insertion RMS Forces	0.174	0.287*	0.020	0.048	0.626*		
TP #1 Insertion RMS Torques	0.1406	0.070	-0.149	0.045	0.728*	0.543*	
TP #2 Insertion RMS Torques	0.284*	0.089	-0.110	0.025	0.537*	0.596*	0.650*

*1-Tailed Significance at 0.001

TP #1 and #2 Insertion Success rates were not correlated to each other or to the other dependent variables; thus, they were analyzed separately using univariate statistical procedures. Because this is attribute data (values are coded as 0 and 1), Pearson Chi-Square statistics[7] (with Yates correction) were calculated. Task Duration and C-H rating were correlated to each other but not to the other dependent variables; thus, these variables were analyzed together using Multivariate Analysis of Variance (MANOVA) statistical procedure.[8] The RMS Force and Torque variables were correlated and should be analyzed together using multivariate statistical procedures. However, all four dependent variables could not be analyzed together because of limitations in the statistical analysis software used. Therefore, two MANOVA statistical procedures were run. One analysis used the RMS Force and Torque at the end effector for the TP #1 Insertion, and a separate analysis was used with the RMS Force and Torque at the end effector for the TP #2 Insertion. Because of the increased error associated with running multiple tests with correlated variables, a more stringent *p*-value of 0.01 was required to accept the difference as statistically significant. A significance level of 0.05 was used for the other procedures.

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[7]Hicks, C. R. (1973). *Fundamental concepts in the design of experiments* (2nd ed.). NY: Holt, Rinehart and Winston.

[8]Chatfield, C. and Collins, A. J. (1980). *Introduction to multivariate analysis.* London: Chapman and Hall.

Kolmogorov-Smirnov Goodness of Fit tests[9] were run on these dependent variables. The results of these analyses indicated that the distributions of these dependent variables are not significantly different from the normal distribution.

The data analysis results are presented in the following sections grouped by research issues (independent variables), instead of being grouped according to the statistical test procedures run. Appendix E contains statistical tables with test statistics and significance level per dependent variable.

3.3.1 Between Subjects Effects

Pearson Chi-Square statistics showed no statistically significant between-subjects effect on ability to successfully perform TP #1 Insertion (Chi-Square statistic = 18.96, $p = 0.062$) or TP #2 Insertion (Chi-Square statistic - 12.20, $p = 0.349$). MANOVA results showed significant between-subjects effects for:

- Task Duration and C-H rating (Pillai's Trace statistic = 0.918, $p = 0.000$; Task Duration F = 57.265, $p = 0.000$; C-H rating F = 110.155, $p = 0.000$);
- RMS Force and Torque levels for TP #1 Insertion (Pillai's Trace statistic = 0.90983, $p = 0.000$; RMS Force F = 62.4506, $p = 0.000$; RMS Torque F = 12.8551, $p = 0.009$); and
- RMS Force and Torque levels for TP #2 Insertion (Pillai's Trace statistic = 0.89204, $p = 0.001$; RMS Force F = 57.5600, $p = 0.000$; RMS Torque F = 16.5296, $p = 0.005$).

3.3.2 Reference Frame Condition

Pearson Chi-Square statistics showed no statistically significant effect of reference frame on the ability of the subjects to successfully perform TP #1 Insertion (Chi-Square statistic = 1.48, $p = 0.224$) or TP #2 Insertion (Chi-Square statistic = 2.53, $p = 0.112$). Reference frame had a statistically significant effect on Task Duration (F = 13.849; $p = 0.004$). The average Task Duration according to reference frame condition is graphed in Figure 3-5. As illustrated, the World reference frame required approximately 43% more time than the End Effector reference frame.

The Task Duration data was divided into four discrete task segments to better understand the effect of reference frame condition on amount of time required to complete the task. Two of the task segments are time to insert the ORU in each receptacle, referred to as TP #1 Insertion Duration and TP #2 Insertion Duration. The remaining two task segments are time to slew between the two task panels. Slew #1 Duration refers to the time required to slew from Task Panel #2 to Task Panel #1. Slew #2 Duration refers to the time required to slew from Task Panel #1 back to Task Panel #2. (refer to Figure 3-1 for the configuration of PFMA and task panel).

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[9]Norusis, M. J. (1986). *SPSS/PC+ for the IBM PC/XT/AT.* Chicago: SPSS, Inc.

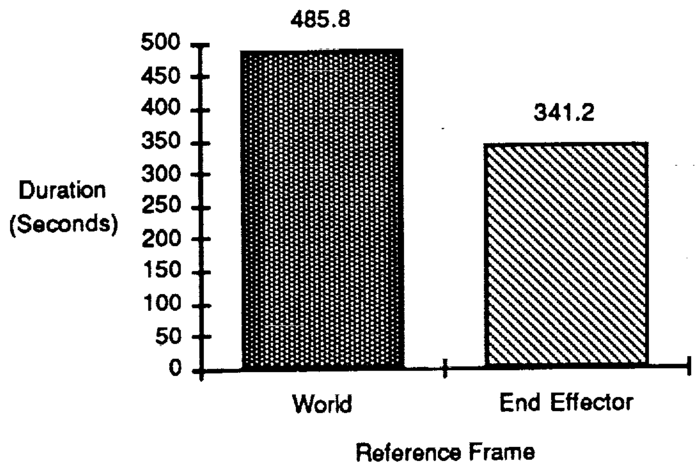

Figure 3-5. Task Duration per Reference Frame.

Figure 3-6 shows the average time required for each task segment by reference frame condition. As shown by this figure, there is no difference between reference frame conditions in the amount of time required to complete Slew #2 or TP #1 Insertion. This result is understandable because both reference frames were aligned when the end effector was pointed at the destination—namely, TP #1. The difference between the two reference frame conditions is due to Slew #1 (from TP #1 to TP #2) and TP #2 Insertion requiring more time with the World reference frame versus the End Effector reference frame. The destination for Slew #1 and TP #2 Insertion is yawed approximately 45-degrees to the left of the centerline (X axis). Therefore, when the gripper was oriented towards TP #2, the World and End Effector references were not aligned. Thus, the World reference frame required more time to perform those task segments where the reference frame were not aligned with the end effector.

A significant effect of reference frame on C-H rating was also found (F = 18.190; p = 0.002). Figure 3-7 shows the average C-H rating per reference frame condition. As shown by this figure, the World reference frame was perceived as more difficult than the End Effector reference frame. Since the World reference frame was perceived as more difficult, it can be hypothesized that the World reference frame required more time to perform the task because it required more cognitive processing.

There was no statistically significant effect of reference frame for TP #1 or #2 Insertion RMS Force and Torque levels (TP #1 Pillai's Trace value = 0.041, p = 0.881; TP #2 Pillai's Trace value = 0.541, p = 0.097).

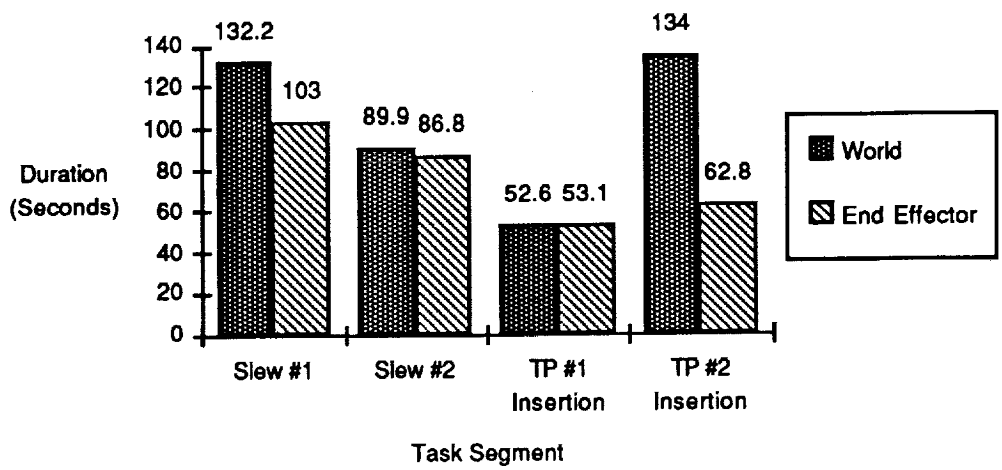

Figure 3-6. Task Duration by Task Segments.

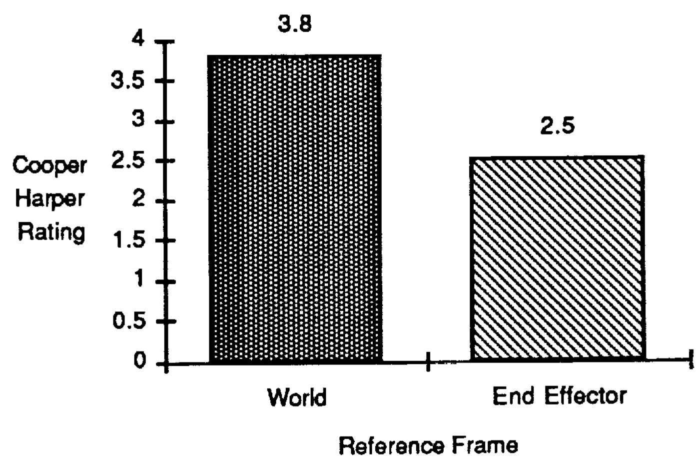

Figure 3-7. Cooper Harper Rating per Reference Frame.

Post test questionnaire results showed that 11 of the 12 operators (91.7%) preferred using the End Effector reference frame for performing the ORU replacement task. The subjects were also asked to rate how strongly they preferred one reference frame over the other reference frame. The strength of preference was rated on a scale from "0" to "3" with "0" for no, "1" for slight, "2" for moderate, and "3" for strong preference. The average preference rating was 2.4, indicating a moderate to strong preference for the End Effector reference frame. The one person who preferred the World reference frame rated his/her preference strength as a 3.

The post-test questionnaire asked the operators to indicate what reference frame they preferred for the two different task segments—slewing and fine alignment—and the strength of their preference. Nine out of 12 operators preferred the End Effector reference frame for slewing and the average degree of preference was a 2 (moderate). The remaining 3 operators who preferred the World reference frame for slewing had a average preference strength rating of 1.3 (slight to moderate). The difference between the two preference strength ratings were not statistically significant ($F = 1.15$; $p = 0.31$). All of the operators preferred the End Effector reference frame for fine alignment and the average strength of this preference was 2.7 (moderate to strong).

The operators were also asked to indicate why they preferred one reference frame over the other. In general, the operators indicated that the End Effector reference frame was easier to use, felt more natural, required less mental effort, and was more responsive. The reason for preferring the World reference frame was that it allowed pre-planning and provided an easier mental model.

3.3.3 Impedance Level Condition

Pearson Chi-Square statistics showed no statistically significant effect of Impedance level on TP #1 or TP #2 Insertion Success rate (TP #1 Chi-Square statistic = 3.05, $p = 0.081$; TP #2 Chi-Square statistic = 0.60, $p = 0.438$). No statistically significant effects due to impedance level was found for either Task Duration or C-H rating (Pillai's Trace value = 0.389, $p = 0.109$). There was no statistically significant effects of impedance level for TP #1 or #2 Insertion RMS Force and Torque levels at the gripper (TP #1 Pillai's Trace value = 0.332, $p = 0.298$; TP #2 Pillai's Trace value = 0.337, $p = 0.292$).

The operators were asked on the post-test questionnaire if they were able to distinguish between the two levels of impedance. Five of the 12 operators (41.7%) indicated that the difference between the two levels was noticeable. Of the 5 subjects who noticed the difference in impedance levels, 3 indicated a preference for the "stiff" impedance for performing the task and gave an average rating of the strength of their preference as a 2 (moderate). The 2 subjects who preferred the "soft" impedance also gave a 2 as the average strength of their preference.

The operators were also asked to indicate which impedance level was preferred for the different task segments. Three of the 5 operators preferred the "stiff" condition for slewing and gave an average preference strength rating of 1.33 (none to slight). The 2 operators who preferred the "soft" condition for slewing gave an average preference strength rating of 1.5 (1 subject rated no preference and one rated a slight preference). For fine alignment tasks, 4 of the 5 preferred the "soft" impedance and gave an average preference strength rating of 3 (strong). The 1 subject that preferred the stiff condition gave an average strength rating of 2 (moderate).

The subjects were asked to indicate the reason for preferring one impedance level over the other. The main reason expressed for preferring the "stiff" impedance condition was that it was more responsive to small motions without overshooting. The main reason for preferring the "soft" impedance condition was that it had a more natural, relaxed feel.

3.3.4 Time Delay Effect

Pearson Chi-Square tests indicated no statistically significant effect of time delay on the ability of the subjects to successfully perform TP #1 or #2 Insertion (TP #1 Chi-Square statistic =4.62, $p = 0.100$; TP #2 Chi-Square statistic = 3.90, $p = 0.142$). A MANOVA analysis found that time delay had a statistically significant effect on Task Duration and C-H rating (Pillai's Trace value = 0.855, $p = 0.000$; Task Duration F = 28.703; $p = 0.000$; C-H F = 24.177; $p = 0.000$).

The average Task Duration according to time delay condition is shown in Figure 3-8. As shown in this graph, the time required to complete the task increased as delay increased. The increase between no time delay and 1 second of time delay (approximately 45% increase) is much larger than the increase between 1 second and 2 seconds (approximately 16% increase). Thus, the increase of time delay (up to 2 seconds) appears to degrade performance less than the addition of time delay.

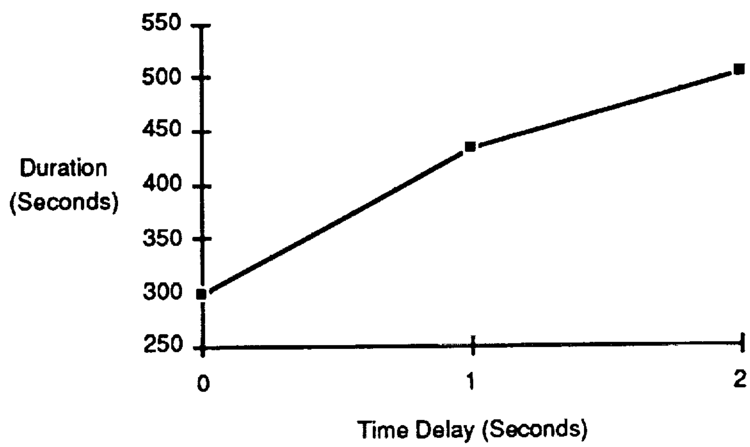

Figure 3-8. Task Duration by Time Delay Condition.

The Task Duration data was divided into the four task segments defined in Section 3.3.2. Figure 3-9 shows the average amount of time to complete each segment per time delay condition. As shown by this figure, the increase in time delay affected the amount of time required to complete Slew #1 the most. Slew #1 was the first slew that the operators performed. It is feasible that this task segment was affected more by time delay than the other segments simply because of the effect of learning. Once the operators became accustomed to the presence of time delay, as the task progressed, it may have influenced performance less.

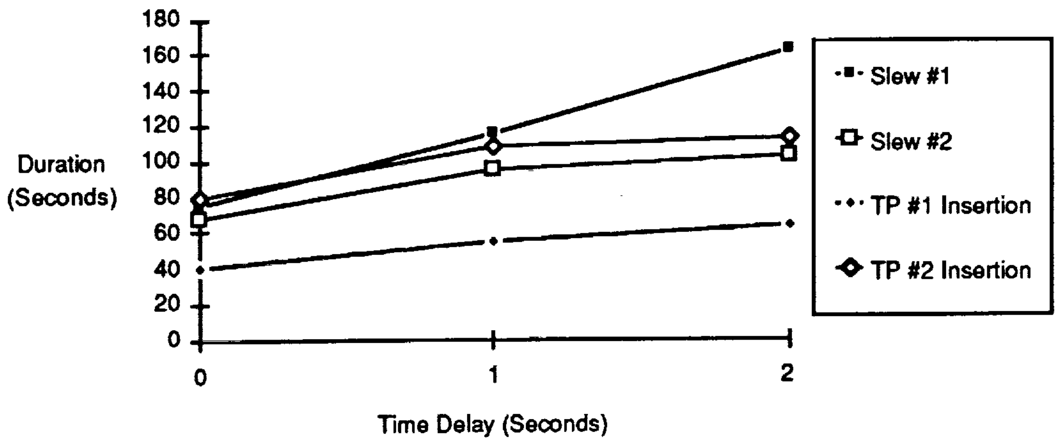

Figure 3-9. Task Segment Duration by Time Delay Condition.

As already mentioned, the MANOVA showed a statistically significant effect of time delay on C-H rating. Figure 3-10 shows the average C-H rating per time delay condition. As shown by this figure, the operators' perception of task difficulty increased as the time delay increased. Since the subjects required more time to perform the task and the task was perceived as more difficult as time delay increased, it can be hypothesized that more cognitive processing was required as time delay increased.

There were no statistically significant effects of time delay for TP #1 or #2 Insertion RMS Force and Torque levels (TP #1 Pillai's Trace statistic = 0.241, $p = 0.854$; TP #2 Pillai's Trace statistic = 0.831, $p = 0.076$).

All 12 of the subjects indicated on the post-test questionnaire that they were able to distinguish between the time delay conditions. The operators were queried as to the type of strategy they used to accommodate the time delay. In general, the operators indicated that they adopted a move and wait strategy, and made smaller, more precise, single axis inputs. Four of the operators adopted a strategy where they actually estimated or timed the delay and paced the lag between their inputs to equal the delay. The operators also indicated that the task was more time consuming and required more thought with time delay than without time delay. The subjects were also asked to recommend methods for making the task easier to perform in the presence of time delay. All of the suggestions inferred the use of a predictive display.

3.3.5 Interaction Effects

The results of MANOVA analyses indicated no two- or three-way interaction effects for Task Duration, C-H rating, TP #1 Insertion RMS Force and Torque levels, or TP #2 Insertion RMS Force and Torque levels. See Appendix F for the Pillai's Trace and p values.

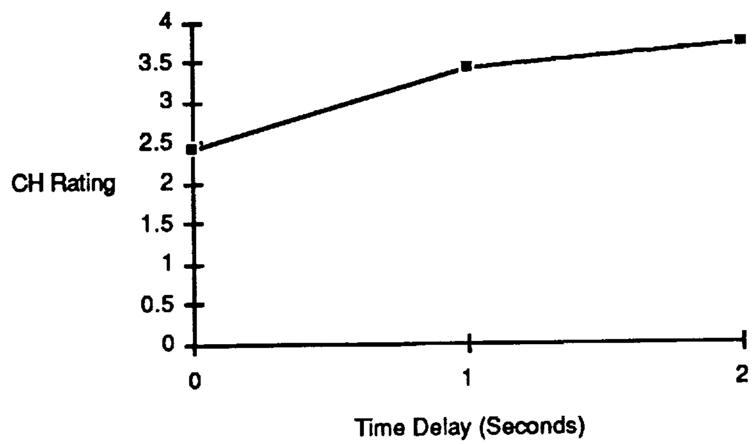

Figure 3-10. Cooper Harper Rating by Time Delay Condition.

The post-test questionnaire asked the subjects to indicate the reference frame that they would prefer under the different combinations of delay and impedance condition. Regardless of the combination of conditions, 9 of the subjects preferred the End Effector reference frame and 1 preferred the World. One subject preferred the World reference frame when there was no time delay and preferred the End Effector reference frame in the presence of time delay. No clear trends emerged when the subjects were asked to selected the preferred impedance condition per combination of reference frame and time delay conditions.

3.3.6 Predictors of Operator Performance

Each subject completed a background questionnaire that asked for information such as how many years s/he has had a drivers' license, previous experience playing video games, and experience controlling remotely controlled models. (The background questionnaire is located in Appendix B). Stepwise regression analyses were performed to determine if there were any background characteristics of the subjects that would predict the amount of time required to perform the task (Task Duration) and the perceived difficulty of the task as measured by a C-H rating (the two dependent variables that were affected by the experimental conditions).

The results of the regression analysis on Task Duration yielded no factors that predicted performance. The results of the regression analysis on C-H rating yielded two factors that predicted subjective assessment of task difficulty. The number of years that the operator had a drivers license accounted for 58% of the variance in the data; the addition of the person's college major into the regression equation accounted for a total of 789% of the variation in the data. There was a negative correlation between the number of years that the person has had a driving license and the C-H rating; thus, the longer the person had a drivers license, the easier they tended to rated the task difficulty. With regard to college major, subjects whose major was Management Information Systems (MIS) tended to rate the task easier than those subjects in other disciplines (e.g., physics, math, and engineering).

3.4 Discussion

High between-subjects variability was noted for all of the dependent variables, except ability to successfully insert the ORU into the task panel receptacles. This points out the need for using a within-subjects experimental design for research of this type to account for the between-subjects variability.

The End Effector reference frame required approximately 43% less time than the World reference frame to perform the ORU insertion task and all but one subject had, on the average, a moderately strong preference for the End Effector reference frame. When the task duration data was viewed by task segments, it was observed that the World reference frame required more time to perform those task segments where the reference frame was not aligned with the end effector. The subjective responses showed that the majority of the operators preferred the End Effector reference frame for the slewing portion of the task, all of them preferred it for the fine alignment portion. This indicates the importance of controlling a manipulator about a point that has relevance to the task being performed.

The World reference frame was rated as significantly more difficulty than the End Effector reference frame. In light of this fact, it is possible that the World reference frame required more time because it required more cognitive processing. This is supported by the post-test questionnaire responses where the subjects indicated that the End Effector reference frame was easier to use and required less mental effort.

No objective performance differences were observed between the impedance conditions and no clear subjective results emerged. Only 5 of the 12 (41.7%) operators indicated that they noticed a difference between the two conditions. Of those 5 subjects, 3 preferred the "stiff" condition and 2 preferred the "soft" condition. Additionally, the strength of their preference was "none" to "slight." No differences may have been noted because there was not enough variability between the two conditions.

Time delay had a statistically significant effect on time to complete the task, such that there was approximately a 45% increase from the no time delay condition to 1 second of time delay and approximately a 16% increase from the 1 second to 2 second time delay conditions. Analysis of the different task segments showed that Slew #1—slew from TP #1 to TP #2—was affected the most by time delay. It is possible that this task segment was most affected simply because of the effect of learning, since this was the first task segment.

Not only did the amount of time required to perform the task increase with time delay, but also the operator's subjective assessment of task difficulty (C-H rating) increased. This is in concert with the operators' responses that the task was more time consuming and required more thought with time delay than without any time delay. When queried as to the type of strategy used to accommodate the time delay, the operators stated that they adopted a move and wait strategy and made smaller, more precise, single axis inputs. The subjects also indicated that the a predictive display would make the task easier to perform in the presence of time delay.

None of the background information gathered from the subjects helped predict task performance as measured by Task Duration. However, the number of years that the person has had a drivers license and s/he's college major did predict subjective assessment of task difficulty, as given by a C-H rating. In general, the longer the person has had a drivers license, the easier s/he rated the task and MIS majors rated the task easier than other majors (e.g., physics, math, and engineering).

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Appendix A – Informed Consent Form

INFORMED CONSENT FORM

Teleoperation Study: Proto-Flight Manipulator Arm at Marshall Space Flight Center (MSFC)

I agree to participate in the above study being conducted by Martin Marietta Astronautics Group in conjunction with Marshall Space Flight Center, involving the operation of the Proto-Flight Manipulator Arm (PFMA). The research team has provided a general overview of the tasks that I will be asked to perform. I understand that participation is voluntary and that I may discontinue the study at any time. All information will be collected on an anonymous basis, which will ensure confidentiality.

I understand that I will be paid $10.00 per hour for my participation in this study. I also understand that payment will be made by means of a check that will be mailed to the address provided below.

SIGNATURE: ______________________________

NAME (PRINTED): ______________________________

DATE: ______________________________

ADDRESS: ______________________________

____

____

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38 INTENTIONALLY

Appendix B – Background Questionnaire

Col.

Subject # ______ 1-2

BACKGROUND INFORMATION

Age: ______ ______ 4-7
Years Months

What is your class standing? (check one) 9

1. ______ Freshman
2. ______ Sophomore
3. ______ Junior
4. ______ Senior
5. ______ Master's level graduate student
6. ______ Ph.D. level graduate student

What is your major?______________________ 11

What is your area of specialization or emphasis (e.g., robotics, artificial intelligence)?______________________ 13

Do you have a driver's license? (check one) 15

1. ______ Yes
2. ______ No

If you answered "Yes" to the previous question, how many years have you had a driver's license? ______________ 17-18

Do you have a pilot's license? (check one) 20

1. ______ Yes
2. ______ No

If you answered "Yes" to the previous question, approximately how many hours have you logged as pilot-in command or as co-pilot? ______________ 22-25

Do you play video games that use a joystick or trackball? (check one) 27

1. ______ Yes
2. ______ No

If you answered "Yes" to the previous question, how many hours per month (on the average) do you normally play? 29-31

Have you ever flown radio-controlled models (e.g., boats, airplanes, cars)? (check one) 33

1. ______ Yes

2. ______ No

If you answered "Yes" to the previous question:
Approximately how many hours have you logged? ______ 35-38
What type of controller did you use? (check one) 40

1. ______ Joystick
2. ______ Wheel
3. ______ Other - Please specify - ______________________________
____
____

Have you ever run the Proto-Flight Manipulator Arm (PFMA) with a hand controller before? (check one) 42

1. ______ Yes
2. ______ No

If you answered "Yes" to the previous question:
How long ago was your experience? ______________ Years ________ Months 44-48
How many total hours did you spend running the PFMA? ____ 50-53

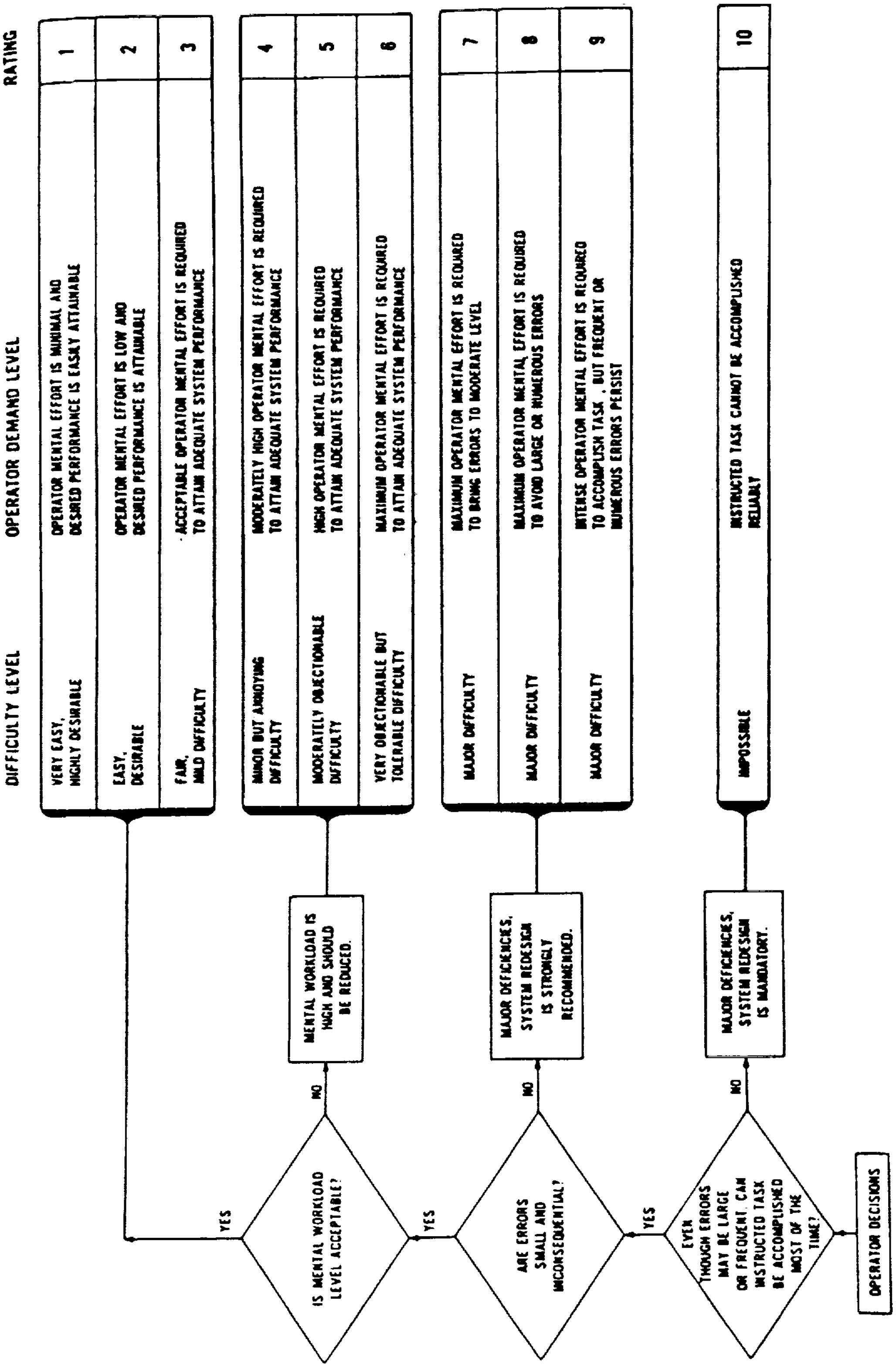
Have you ever used a hand controller like the one shown to you? (check one) 55

1. ______ Yes
2. ______ No

If you answered "Yes" to the previous question:
How long ago was your experience? ______________ Years ________ Months 57-61
How many total hours did you spend using the hand controller? ______________ 63-66
For what purpose did you use the hand controller? ______________________ 68
____
____

***** THANK YOU!!! *****

Appendix C – Cooper-Harper Rating Scale



Appendix D – Post-Test Questionnaire

Subject #____

POST-TEST QUESTIONNAIRE

Please answer the following questions as thoroughly as possible. If you require more space, use the back of the page. If you have any questions, please ask one of the test conductors for assistance.

The questions ask you to consider not only the overall task, but also different parts of the task you performed. The parts you are asked to consider are the Slewing and Fine Alignment task parts. Slewing refers to such motions as moving the box from one location to another location. Fine Alignment refers to such motions as placing the box in or removing it from the task panel. Slewing motions consist of larger, less precise movements. Fine Alignment motions consist of smaller, more precise movements.

REFERENCE FRAME

World reference frame refers to the reference frame that was located above and behind the manipulator arm.

End Effector reference frame refers to the reference frame that was located near the manipulator's end effector.

	Overall Task	**Slewing**	**Fine Alignment**
Which reference frame do you prefer? Write *World* or *End Effector* in the blanks provided.	______	______	______
How strongly is your preference? Use the following numbers to indicate level of preference: *0* = none *1* = slight *2* = moderate *3* = strong	______	______	______

Why do you prefer this reference frame?

Example responses:

"easy to use"

"felt natural"

"more controllable"

"more responsive"

______	______	______
______	______	______
______	______	______
______	______	______
______	______	______

IMPEDANCE

	Overall Task	Slewing	Fine Alignment
Which impedance do you prefer? Write *Soft* or *Stiff* in the blanks provided.	______	______	______
How strongly is your preference? Use the following numbers to indicate level of preference: *0* = none, *1* = slight, *2* = moderate, *3* = strong	______	______	______

Why do you prefer this impedance?

Example responses:

"easy to use"

"felt natural"

"more controllable"

"more responsive"

______	______	______
______	______	______
______	______	______
______	______	______
______	______	______

TIME DELAY

Were the different time delays noticeable? (check one)

1. ______No
2. ______Yes

What type of strategy did you use to accommodate the time delay?

____

____

____

What difference did the time delay make in terms of the way that you performed the task?

____

____

____

What could have been done to make it easier for you to perform the task with time delay?

____

____

____

Please fill out the following matrices as best as you can.

Under the following combinations, which reference frame did you prefer for the overall task? (write *World* or *End Effector* in each cell)

	Soft Impedance	Stiff Impedance
No Time Delay		
Some Time Delay		
Most Time Delay		

Under the following combinations, which impedance did you prefer for the overall task? (write Soft or Stiff in each cell)

	World Reference Frame	End Effector Reference Frame
No Time Delay		
Some Time Delay		
Most Time Delay		

____

Appendix E – Statistical Tables per Dependent Variable(s)

P-values that are less than or equal to 0.05 have an asterisk * behind them.

Table E-1. Pearson Chi-Square Table for TP #1 Insertion Success.

FACTOR	CHI-SQUARE VALUE	*p*-VALUE
Between Subjects	18.96	0.062
Within Subjects		
Reference Frame	1.48	0.224
Impedance	3.05	0.081
Time Delay	4.62	0.100

Table E-2. Pearson Chi-Square Table for TP #2 Insertion Success.

FACTOR	CHI-SQUARE VALUE	*p*-VALUE
Between Subjects	12.20	0.349
Within Subjects		
Reference Frame	2.53	0.112
Impedance	0.60	0.438
Time Delay	3.90	0.142

Table E-3. MANOVA Table for Task Duration and CH Rating.

FACTOR	PILLAI'S TRACE VALUE	F VALUE	*p*-VALUE
<u>Between Subjects Effect</u>	0.918		0.000*
Duration		57.265	0.000*
Cooper Harper		110.155	0.000*
<u>Within Subjects</u>			
Main Effects			
Reference Frame	0.649		0.009*
Duration		13.849	0.004*
Cooper Harper		18.190	0.002*
Impedance	0.389		0.109
Time Delay	0.855		0.000*
Duration		28.703	0.000*
Cooper Harper		24.177	0.000*
Interaction Effects			
Frame x Impedance	0.078		0.695
Frame x Delay	0.362		0.471
Impedance x Delay	0.251		0.684
Frame x Impedance x Delay	0.574		0.151

Table E-4. MANOVA Table for RMS Force and Torque for ORU #1 Insertion.

FACTOR	PILLAI'S TRACE VALUE	F VALUE	*p*-VALUE
<u>Between Subjects Effect</u>	0.910		0.001*
RMS Force		62.451	0.000*
RMS Torque		12.855	0.009*
<u>Within Subjects</u>			
Main Effects			
Reference Frame	0.041		0.881
Impedance	0.332		0.298
Time Delay	0.241		0.854
Interaction Effects			
Frame x Impedance	0.385		0.232
Frame x Delay	0.725		0.185
Impedance x Delay	0.268		0.823
Frame x Impedance x Delay	0.405		0.641

Table E-5. MANOVA Table for RMS Force and Torque for ORU #2 Insertion.

FACTOR	PILLAI'S TRACE VALUE	F VALUE	*p*- VALUE
Between Subjects Effect	0.892		0.001*
RMS Force		57.560	0.000*
RMS Torque		16.530	0.005*
Within Subjects			
Main Effects			
Reference Frame	0.541		0.097
Impedance	0.337		0.292
Time Delay	0.831		0.076
Interaction Effects			
Frame x Impedance	0.194		0.523
Frame x Delay	0.392		0.660
Impedance x Delay	0.531		0.454
Frame x Impedance x Delay	0.721		0.190